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Sense and movement. Design of a system for sensorimotor rehabilitation after stroke.

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Abstract: The paper presents the preliminary research for the development of a technologically advanced system that aims to introduce earlier treatment in the rehabilitative process of patients in a bedridden condition because of a stroke attack. After an overview on stroke and the principles of rehabilitation based on academic literature on biomedical engineering and neurosciences, the research focuses on the state of art of the rehabilitative instruments used to stimulate the brain: environment and interaction have a strong impact on daily experience in terms of cognitive response and ability to rewire the brain, therefore rehabilitation can be considered a particular experience that needs to be designed with attention to human factors. The paper gives an overview on the technologies in use and in the final section of the paper introduces the considerations and methodologies based on which a technologically advanced rehabilitative system will be developed.

Keywords: Sensorimotor rehabilitation, Human-centered design, Neural plasticity, Robotics, Serious game

1. Introduction

Stroke is the third cause of death and the first cause of disability in the world. The consequences of stroke in terms of disabilities cannot be collected in a sample because stroke victims vary widely by age, sex and symptoms. In the rehabilitation process, the physician helps the patient to recover his ability as fully and as quickly as possible. Given the variety of symptoms, the therapy must be developed individually for each patient on an experimental basis, with results and interactions that cannot always be measured with scientific criteria.

This paper focuses on sensorimotor rehabilitation after a stroke, exploring how design can interact with medical practices and biomedical engineering by applying innovative technologies – such as robotics and virtual or augmented reality – to improve the patient's rehabilitative experience.

Designing a product or environment may be described as the development of an experience of interaction that can stimulate an emotional and cognitive reaction in the user, leading to further

interactions and a predisposition to use the object or relate to the environment. The role of design in the medical field has largely been limited to an aesthetic contribution on supports for disabilities and the introduction, in isolated cases, of technological innovation. But design can play an important role in a context such as stroke rehabilitation, where it can help to redefine the patient's cognitive maps by stimulating specific movements, thereby increasing the efficiency of the therapy.

The research began with an overview of stroke and the principles of rehabilitation based on academic literature on neurosciences to identify the context and explain basic concepts on which the topic will be discussed.

The results of stroke rehabilitation depend to a great extent on the patient experience in relation to these dynamics, and on medical devices that merge medical and engineering expertise with human factors: the strongpoint of design is its ability to find a meeting point between these different disciplines to create a synthesis and serve as a connector between advanced technologies, the neurosciences and user needs.

Neuroscientists have been studying the effects of the environment on the mind, demonstrating that a person's experience of the world influences his brain and abilities. The contribution of design to the development of medical devices for stroke rehabilitation can be important because it designs the object as well as the experience for both the patient and the physician, transferring technology and knowledge tested and developed in other fields into the development of rehabilitative instruments.

A further step was the analysis of the literature from biomedical engineering and neurosciences about the dynamics of rehabilitation, the applied technologies and the identification of problematic areas, followed by an on-field observation of the rehabilitation process supported by technological medical devices, which was important to visualize the dynamics between the physician, the patient and the instrument.

The meaning of the work lies in the parallel development of a theorization of design's relevance in a field where developers largely come from scientific disciplines and the application on the design of a system of methods based on human factors, such as aesthetic affordances and usability, that emphasize results which are not measurable only by common scientific methods.

2. Context

2.1 Stroke

Stroke is a cerebrovascular disease that represents the first cause of disability and the third of death worldwide (Taylor, 2015; Vallar & Papagno, 2007). Risk factors for ischemic stroke can be non-modifiable, such as age, sex, race, genetic structure, or modifiable such as arterial hypertension, cardiac diseases, diabetes, obesity, smoke or alcohol abuse; the most frequent cause of haemorrhagic stroke is arterial hypertension, followed by the breakage of aneurisms and a 2% of arteriovenous malformation (AVM). Even if the latter can be considered the less likely to occur, it is the most common cause of stroke among people from 25 to 45 years old (Taylor, 2015).

The impact of stroke changes depending on the extension and the area of the brain in which the trauma takes place, the consequences are different and need a different therapeutic approach. The model for the therapy is the same used for neurological exams: it contemplates the collection of the patient's clinical history (anamnesis); if possible, a talk with the patient; administration of a test to register qualitative data about the behaviour; and it ends with a talk with the family in order to check the patient's conditions before the stroke, the possibilities to get proper assistance and the recovery

expectations. The collection of this data helps to get an overview on the patient and to develop a customized therapy. The clinical effects of the treatments are monitored through psychometric tests, while the ecological effects related to daily activities are evaluated with scales rating disability and independence (Vallar & Papagno, 2007). Due to the specificity of the interventions, the studies about cognitive rehabilitation therapy are carried out on single cases, so they can be considered experimental and rely on an intra-subject analysis (Vallar & Papagno, 2007). The necessity to deal with every single case without external terms of comparison makes it difficult to match the results and quantify them according to standard methodologies, but there is evidence (Vallar & Papagno, 2007) that intensive care, even if practiced for a short time, is more effective than treatments a few hours long repeated with constancy.

2.2 Rehabilitation

The scope of rehabilitation after a stroke is to induce a recovery greater than one that can be achieved spontaneously, and the course of this pathology can correspond to an almost complete recovery. A spontaneous recovery can occur up to six months after the advent of the stroke (Vallar & Papagno, 2007), however a complete recovery can be achieved in few years and the entire process requires the patient's strong will, external stimulus and assistance (Taylor, 2015).

The rehabilitative intervention is a preventive measure to give psychological support to the patient and his family, it quickens the recover to avoid the onset of secondary disabilities and associated diseases, but above all it aims to provide a better quality of life to the patient through the management of the residual disability.

The goal of sensorimotor therapy is to recover movement by stimulating cognitive functions instead of muscular strength, it requires proper support structures and immediate assistance to avoid the formation of falsified sensory maps that could slow down the recovery. Indeed, the neurological principle on which the rehabilitation is built is neuroplasticity, the ability of the brain to supply the function of the damaged area by rewiring the neural net (Biondi, Rognoli, & Levi, 2010, p. 23; Doidge, 2013, p. 9; Goewey, 2014, p. 9; Taylor, 2015, p. 36).

The therapy is organized in three stages, corresponding to the course of the pathology, and the patient's response to the therapy can be of three types. The rehabilitative project is established on the basis of the patient's needs and preferences, his clinical condition, on the outcomes and expectations defined in relation to the patient's lifestyle before the advent of the stroke and on the assistance the interdisciplinary medical team can offer.

3. Approach and assumptions

Rehabilitation after stroke is considered here as an experience of interaction with the environment and specific devices with the aim to achieve patient recovery. If we consider that as something that needs to be designed, the main research question might be how can the designer apply knowledge from neurosciences and biomedical engineering to develop products that improve the therapy, followed by a focus on what knowledge is relevant in this process of product development.

The approach adopted to deal with this topic is human-centred: neuroscientists have been studying the effects of the environment on the mind, demonstrating that a person's experience of the world influences his brain and abilities. If we consider that "most of the advances in medicine are related to medical technology" (Perez, 2002, p. 1) and that technology is perceived by the patient as a

guarantee of efficacy (*Dalla cura delle cose alla cura delle persone. Il disegno industriale per la sanità*, 1999, p. 15), it is evident that the design of a rehabilitative system can play an important role in the sensorimotor therapy in terms of acceptability, usability and motivation. Human factors, intended here as synonymous of ergonomics following the definition given by Sanders (Sanders, 1993, p. 4), gives “emphasis on human beings and how the design of things influences people”, and it is important to distinguish this approach from the user-centred one because in this case the design does not address the users in functional terms (Anselmi, 2010, p. 63) but their experience of rehabilitation.

To have a visual overview of the patient’s experience, the creation of a patient journey is a useful step. The journey starts when the patient enters the healthcare facility: more or less conscious, she goes through bureaucratic procedures, hospitalization, recovery and follow-ups, and the environment has a strong impact on her physical and psychological orientation such as her emotional response. Developing the map, emphasis should be placed on the environment, the physicians, the carers, the family and all the other figures involved in the patient’s treatment since they are relevant actors playing different roles in the rehabilitative process of the patient: in the phases of hospitalization and in the following stages where the patient is not independent, they are the main users of the instruments around the patient, who becomes the beneficiary of the interaction instead of being the user.

The impersonality of the environments and the lack of communication between physician and patient have been identified as the main problem of hospitalization (Iaconesi & Persico, 2016; Maiocchi, 2010, p. 19): it’s not only about understanding the disease and how to treat it, but the necessity of the patient to feel considered as an independent self and not merely the carrier of a disease.

The emotional response to the environment is relevant in terms of the impact of feelings on the structure of the brain, because the perception and the interaction with the surroundings are strictly connected to the cultural background and to the capacity of the brain to rewire itself (Clark, 2004, p. 84; Doidge, 2013, p. 7; Goewey, 2014, p. 9). For a long time, the relation between the brain and the environment has been indirectly addressed by different disciplines, from philosophy to anthropology, but was proven to be a neural process with the discovery of mirror neurons at the end of the XX century (Rizzolatti & Sinigaglia, 2006) and defined with the term “embodiment”. In this essay, the term embodiment is addressed as a process that identifies consciousness across the brain-body world division, as proposed by Thompson and Varela (Mallgrave, 2015, p. 83; Thompson & Varela, 2001), and it is used to express the capability of the brain to learn in a continued sensorimotor interaction with the world (Benasayag, 2016, p. 58; Clark, 2004, p. 83).

As the environment has an influence on the human behaviour, the relationship with objects brings the embodiment to another level of intimacy: instruments and decorative objects have been built over time to meet biological and social needs, improving functional and aesthetic features with the succession of discoveries of materials and productive techniques. If the aspect of some elements could give immediate feedback to the brain about the function and how to use them, the increasing complexity of objects has started to require training to be able to use specific instruments, and this is particularly evident in mechanical and electronical devices.

The concept of affordance (Gibson, 2014), introduced by Gibson in 1986 as part of the ecological approach of visual perception, has become the reference to understand how the shape of an object can lead to a specific interaction, or serve as a perceptive means that involves the body in the action. A neurological correlation of the affordance can be identified in the mirror neurons (Rizzolatti &

Sinigaglia, 2006, p. 121), that activate in response to perceptive stimulus and are oriented to reproduce an action independently of whether it involves a movement of the body or not. They can codify motor acts selecting the kind of act and the sequence of movements that make it out, and they activate even when the action is mimed: the use of mirror neurons is widely demonstrated in the process of exercise to learn sport practices (Biondi et al., 2010, p. 123; Notarnicola et al., 2014).

The discoveries in the neurosciences about the way the brain works have enhanced awareness of the relevance of emotive qualities in all designed products, and attention has been given to the design for disabilities, monitoring devices and other healthcare products. In particular, qualities to be addressed during the design process are the emphasis on the shape, light and colour of the environments (Meuser, 2011), the quality of the information given to the user and the type of interaction (Maiocchi, 2010, p. 26), and, last but not least, usability (Anselmi, 2010, p. 47).

Usability is a core concept of human factors, defined by international regulations ISO 9247/11 - 98 and EN 6061-1-6:2006, it represents “a measure of the effectiveness, efficiency, and satisfaction with which specified operators achieve specified goals in particular environments, within the scope of the intended use of the equipment”. The wide literature about usability shows that it can be addressed from different points of view: Norman (Norman, 2004, 2015) approaches it in terms of physical and emotive response, Tosi (Tosi, 2006) focuses her attention on the contextualization of ergonomics for design. In the early Nineties, Sanders (Sanders, 1993, p. 9) introduces the design of medical devices and the design of products and facilities for the elderly as areas in which human factors should be involved, underlining how the objectives of human factors are “to enhance the effectiveness and efficiency with which work and other activities are carried out” and “to enhance certain desirable human values, including improved safety, reduced fatigue and stress, increased comfort, greater user acceptance, increased job satisfaction, and improved quality of life” (Sanders, 1993, p. 4). An important addition he gives on the use of human factors is that they are not a collection of checklists or guidelines nor the application of common sense.

Design intervention on technological instruments connected to health is focused on prosthetics (Pullin, 2009), that in some historical periods have been considered as elements to hide, while in other times they have been not only socially accepted but even exhibited as fashion accessories. Indeed, a positive emotional engagement with the prosthetic element is relevant to facilitate the relation between the patient and the supportive technological device: instead of being considered disabled and therefore excluded from social situations, the user’s self-consciousness increases thanks to the interaction with the prosthesis. Spectacles are a good example of this process: thanks to the application of innovative materials and the design of original shapes, they have become a fashionable object that enhances the facial features of the user rather than underlining the visual impairment, and it is not hard to imagine that lumbar implants can face the same customization process in the near future, turning into interchangeable accessories with a strong aesthetic value (Pullin, 2009; Rawsthorn, 2013).

4. Technologies for sensorimotor rehabilitation

4.1 State of the art

Given the relevance of the relation between body and cognition for a correct functioning of the organism, the goal of sensorimotor rehabilitation after stroke is to re-create the connection between sensation and movement through the regular stimulation of both the systems (sensorial and motor)

with different instruments. To get a overview of the state of art of sensorimotor rehabilitation after stroke, a literature study has been conducted.

The literature research has been conducted with an interdisciplinary approach, through a selection of papers related to all the disciplines that might be involved in the rehabilitation, from biomedical engineering to neurosciences but also game development, psychology and social economy. A first criteria of selection has been the identification of applicative reports on sensorimotor stimulation, followed by the reorganization of the material in relation to cognitive or motor disease, to the part of the body addressed (upper limbs, lower limbs) and the precision of the required movement (shoulder, elbow, wrist and hand for the upper limb; hip, knee, ankle and foot for the lower limb). This first organization shows the processes applied to help the brain reset motor skills and makes it possible to identify the approaches shared between the medical community, the scales of reference for the classification of the patient's disability and provides an overview of the technologies applied. The following classification consisted in the partition of the documentation based on the applied technologies (robotics, virtual reality in form of serious game), subsequently further divided in terms of applicative report, experimental report, design oriented report.

The results of the therapy depend on several factors such as the area of the brain affected by the stroke, the immediacy of recovery, the age of the patient, her life condition before the stroke occurrence and her psychological attitude towards the rehabilitation. This last consideration is the one for which designing the interaction can make the difference: as we have seen before, emotions are the consequence of internal and external stimuli, and through the design of an object (or a system) it is possible to drive the emotional response of the user and to get improvement in the performance of a task.

The literature analysis has shown a predominance of a sensorimotor approach towards the rehabilitation of cognitive diseases and upper limbs, probably due to the plurality of cognitive impairments and the higher request of precision skills. Besides, the rehabilitation is more effective if done shortly after the recovery, the rehabilitation of the upper limbs follows that of the lower limbs and might need more effort to achieve recognizable improvements. However, a benchmark analysis of a few robotic instruments used for lower-limb rehabilitation has shown that there's a push to put the patient in a standing position, implying that the body is suspended on huge machinery or forced in exoskeletons. The results of this analysis have been compared with a taxonomy of supportive instruments for walking and cycling in industrial and technical applications (robotic exoskeletons to reduce spinal injuries due to the displacement of high weights), sports (exercising machines such as exercise bikes and treadmills, balance systems integrating virtual reality) and home entertainment (accessories for interactive consoles) in order to get an overview of dimensions, technological content, user's position and interaction.

The outcome of this analysis shows the lack of studies for the development of rehabilitative technologies to be used by a patient in a supine position, the usual condition in the acute and sub-acute phases of the therapy. Even though the clinical condition of the patient in the first phases of the recovery is precarious, those are the moments in which the brain can recover faster if exposed to proper stimuli, and the emergence of studies about the application of virtual reality and interactive environments can play a significant role in the development of technologies that would allow the introduction of sensorimotor rehabilitation earlier in the patient's journey.

4.2 Project development

The outcome of this research is meant to be a system for sensorimotor rehabilitation of bedridden patients, allowing the therapy to start in a sub-acute phase.

The project aims to be an example of the application of design thinking and human factors in the development of technologically advanced systems that influences the neural plasticity in weak subjects. The goal of the project is to leverage empathy to stimulate the sensorimotor system, producing a response of the brain in terms of neural plasticity, helping the patient thanks to an immersive experience of embodiment supported by haptic feedback, and tracking the treatment and the patient's response to give the carer an overview of the rehabilitation and the possibility to customize the exercises in relation to the patient's needs.

The project has been conceived as a system, considered as a process in which “humans, machines and other things work together (interact) to accomplish some goal which these same components could not produce independently”; therefore, the outcome will be “a combination of one or more human beings and one or more physical components interacting to bring about, from given inputs, some desired output”, where the machine “consists of virtually any type of physical object, device, equipment (...) that is directed toward achieving some desired purpose” (Sanders, 1993, p. 14).

The identification of the users is relevant in terms of anthropometric and biomechanical considerations and of interpersonal aspects, all factors to be considered with attention given the context in which they act. In this case, a patient journey is used to identify the actors, the sequence of interaction and the structural needs to be addressed.

The development of the instruments needs to be approached in a systemic way but at the same time each component requires a specific design resulting from the interaction required and the specific placement in the environment of use: the findings of the literature study, the identification of specific issues and users and functional exigencies have been collected in a brief, to focus on the relevant aspects of the interaction that need to be addressed by the system.

Subsequently, a hypothetical architecture of the system was drawn in order to visualize the structure and the components involved in the interaction: there are two users - the patient, beneficiary of the therapy and an operator who supports the interaction and sets up the system - and three different elements of interaction - a robotic element that drives and follows the movements, a visual support that creates the sensorial environment and introduces the serious game, intended as a game that has “an explicit and carefully thought-out educational purpose and is not intended to be played primarily for amusement” (Abt, 1987), and a wearable device that monitors the movement and gives the haptic feedback.

After the definition of the interaction in terms of tasks and biomechanical requirements, the robotic part and the wearable support can be developed. The connected serious game will be developed in parallel, using existing supports to allow customization and reduce the costs of the final product, ensuring its accessibility. The reference models for the serious game are the concept of optimal experience, introduced by Csikszentmihalyi (Csikszentmihalyi, 2009) as a way to enjoy specific activities through flow, and incorporation, introduced by Calleja (Calleja, 2011) with six dimensions of the player's involvement in massively multiplayer on-line games (MMOGs): the virtual experience offered to the patient is going to be functional to stimulate the association of stimulus and movement, at the same time it will give a motivational push through mechanisms of visualization and reward of the progress, the possibility to share the experience among patients in the same condition and to collect the therapeutic path to create a methodological reference to treat this particular aspect of rehabilitation.

5. Conclusions

The methodology used in the research presents an iterative process: the formulation of the project started with a literature research oriented towards the identification of the state of art, followed by an observation of a stroke unit aimed to verify the effective state of the art in public healthcare structures and to draw a complete patient journey; a review of the literature compared to the observation outcomes was conducted to identify the areas in which a design intervention could be relevant; then the project was developed with a brief, the hypothesis of the system architecture and technologies, a benchmark analysis of some of the existing products, followed by sketches focusing on formal, functional and ergonomic aspects. Further steps will be the creation of a mock-up to be introduced to the medical staff and to the patients to verify the acceptability and usability of the system; then the project will be enhanced through the assimilation of the observations of the testing. The following steps will be the engineering, the prototyping and the clinical testing with patients.

The aim of this paper is to present how design and neurosciences can have a mutual influence in terms of interaction and perception of the surroundings. Since the work is still under development, some aspects may need to be defined and some may be found irrelevant for the future application.

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